Modal Mapping Techniques for Geoacoustic Inversion and Source Localization in Laterally Varying, Shallow-Water Environments

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LONG-TERM GOALS

The long-term goal of this research is to increase our understanding of shallow water acoustic propagation and its relationship to the three-dimensionally varying geoacoustic properties of the seabed.

OBJECTIVES

The scientific objectives of this research are: (1) to develop high-resolution methods for characterizing the spatial and temporal behavior of the normal mode field in shallow water; (2) to use this characterization as input data to inversion techniques for inferring the acoustic properties of the shallow-water waveguide; and (3) to use this characterization to improve our ability to localize and track sources.

APPROACH

An experimental technique is being developed for mapping the normal mode field and its wavenumber spectrum as a function of position in a complex, shallow-water waveguide environment whose acoustic properties vary in three spatial dimensions. By describing the spatially varying spectral content of the modal field, the method provides a direct measure of the propagation characteristics of the waveguide. The resulting modal maps can also be used as input data to inverse techniques for obtaining the laterally varying, acoustic properties of the waveguide. The experimental configuration consists of a moored, drifting, or towed source radiating one or more pure tones to a field of freely drifting buoys, each containing two hydrophones, GPS navigation, and radio telemetry, as shown in Fig. 1. A key component of this method is the establishment of a local differential GPS system between the ship and each buoy, thereby enabling the determination of the positions of the buoys relative to the ship with submeter accuracy. In this manner, the drifting buoys create 2-D synthetic aperture horizontal arrays along which the modal evolution of the waveguide can be observed in the spatial domain, or after beam forming, in the horizontal wavenumber domain. In this context, two-dimensional modal maps in range *and* azimuth, as well as three-dimensional bottom inversion in range, depth, *and* azimuth,

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become achievable goals. In addition, these high-resolution measurements have provided significant new insights into source localization and tracking techniques.

WORK COMPLETED

Prior to 2006, three successful Modal Mapping Experiments (MOMAX) were completed. Two of these experiments (MOMAX I and SWAT/MOMAX III) were conducted in the East Coast STRATAFORM/SWARM area off the New Jersey coast and one (LWAD 99-1/MOMAX II) was carried out in the Gulf of Mexico. In these experiments, several drifting MOMAX buoys received signals out to ranges of 20 km from moored, drifting, and towed sources transmitting pure tones in the frequency range 20-475 Hz. In the traditional MOMAX deployment, a source transmits a pure tone (usually several) of precisely known frequency to the MOMAX buoys. The known carrier frequency contribution to the total phase is removed from the measured signal, and the resulting pressure field magnitude and phase versus time data are then merged with the corresponding GPS-derived source-receiver positions versus time. This procedure enables the determination of the pressure magnitude and phase as a function of two-dimensional position. High-resolution beam-forming techniques (corresponding to the application of an asymptotic Hankel transform) and inverse methods are then applied to these synthetic aperture data to obtain the modal information and the geoacoustic properties of the seabed.

On Aug. 30 – Sept. 5, 2006, MOMAX IV was successfully conducted as part of SW06, the ONR-sponsored, multi-institutional, multi-ship, series of shallow-water experiments that were conducted off the New Jersey coast throughout the summer of 2006. A wide range of environmental data was also obtained as part of SW06 that included an extensive suite of physical oceanographic measurements. As a result, a primary focus of SW06/MOMAX IV was the study of the effects of water column variability on the modal inversion process.

SW06/MOMAX IV was conducted aboard the R/V Oceanus, which served as the source ship from which the NUWC J15-3 sound source was suspended from the A-frame at a depth of 60 m. The source transmitted pure tones for a period of approximately 25 hours with frequencies of 50, 75, 125, and 175 Hz. These signals were received by 4 drifting MOMAX buoys, as well as an 8-channel Webb vertical line array (VLA), out to ranges of 10 km. The VLA, with 8 m hydrophone spacing, was deployed during MOMAX IV on Aug. 31 and recovered on Sept. 8 on a subsequent R/V Oceanus cruise.

The MOMAX buoy suspension system, including the locations of the two hydrophones at nominal depths of 40 m and 43 m, is presented in Fig. 2. Also shown is a temperature/pressure module which is mounted directly above the upper hydrophone. Both the VLA and the sound source string were also outfitted with a series of temperature sensors. The ship track, the trajectories of the drifting buoys, and the location of the VLA are illustrated in Fig. 3 and superimposed upon the subbottom river channels present in the area in Fig. 4. Also shown in Fig. 3 are the positions of several environmental and source moorings that were already in place as part of the suite of SW06 experimental assets.

RESULTS

Of particular interest are the effects of the subbottom river channels on low-frequency propagation and geoacoustic inversion. These channels introduce significant lateral variability into the waveguide environment, as shown in Fig. 5. In order to study further the influence of these channels, a careful examination of the 50 Hz data obtained on the 40 m receiver on one of the buoys (Curley), as well as its spatial spectral characteristics, was carried out. The novel 4-quadrant display shown in Fig. 6 brings us much closer to achieving the goal of visualizing the sound field and its relationship to the environment, particularly lateral variation in the subbottom geoacoustic properties. An examination of this figure suggests that the subbottom variability associated with these channels may be the cause of the pronounced variation in the measured autoregressive (AR) wavenumber spectrum versus range (Fig. 6: lower right panel). Specifically, it appears that the second of three modal peaks in the middle AR segment (which corresponds to the receiver traversing a region with no channel) vanishes when the receiver drifts across channels in the outer two AR segments. In addition, the other two modal peaks, which appear in all three AR segments, are shifted as the receiver traverses the Channel/No Channel/Channel regions. A summary of the corresponding environmental variability in the water column and the seabed, as well as its relationship to the three AR processing apertures, is shown in Fig. 7. Sensitivity studies have indicated that water column variability is playing a secondary role in this instance, and therefore the bottom is the primary influence on the modal behavior. Consequently, an iterative inversion scheme was applied to these data in order to determine the differences in the seabed geoacoustic properties between the Channel and No Channel regions, and the results of this effort are shown in Fig. 8. The corresponding comparison between the measured eigenvalues and those computed with the KRAKEN normal mode model using the inverted profiles as input data, are shown in Fig. 9. It is clear that the inferred geoacoustic models are able to reproduce the shifts in modal eigenvalues, but are unable to generate the vanishing mode behavior associated with the presence of a channel. In pursuit of a suitable explanation for the vanishing mode effect, as well as other range-dependent effects in the data, the following avenues of research are currently being pursued: (a) an examination of the channel effects at the 43 m receiver and at the other MOMAX frequencies (75, 125, and 175 Hz); (b) an investigation of the role of mode coupling and acoustic interactions that are coupled between the bottom and the water column; and (c) inversion for improved geoacoustic models in the Channel and No Channel regions.

IMPACT/APPLICATIONS

The experimental configuration consisting of a CW source and freely drifting buoys will provide a simple way to characterize a shallow water area and may be useful in survey operations. In addition, the planar, synthetic receiving array may offer an effective new technique for localizing and tracking sources of unknown, quasi-stable frequency in shallow water.

TRANSITIONS

The synthetic aperture technique and Hankel transform inversion methodology which underlie the modal mapping method have been implemented in the ACT II experiment, sponsored by DARPA and ONR, and have been used in the REMUS towed array experiments being conducted by Carey and Lynch. This approach has also been adopted by several research groups internationally, including the Japanese groups involved in SWAT. The process of transitioning the MOMAX experimental approach and geoacoustic inversion methodology to NAVAIR and NAVOCEANO has been initiated.

RELATED PROJECTS

MOMAX I and III, as well as SW06, were conducted in the same area off the New Jersey coast where the ONR-sponsored STRATAFORM, SWARM, PRIMER, Geoclutter, and Boundary Characterization experiments were carried out. The extensive geophysical, seismic, acoustic, and oceanographic data obtained in this suite of experiments are being used to ground truth the MOMAX measurements.

The SW06/MOMAX IV data analysis and interpretation are being carried out in collaboration with a number of other SW06 investigators, including:

Acoustics: Kyle Becker, Ross Chapman, Harry DeFerrari, Bill Hodgkiss, David Knobles, Jim Lynch.

Geoacoustics: John Goff, Altan Turgut.

Physical Oceanography: Tim Duda, Glen Gawarkiewicz, Scott Glenn, Frank Henyey, Jim Moum, Jonathan Nash.

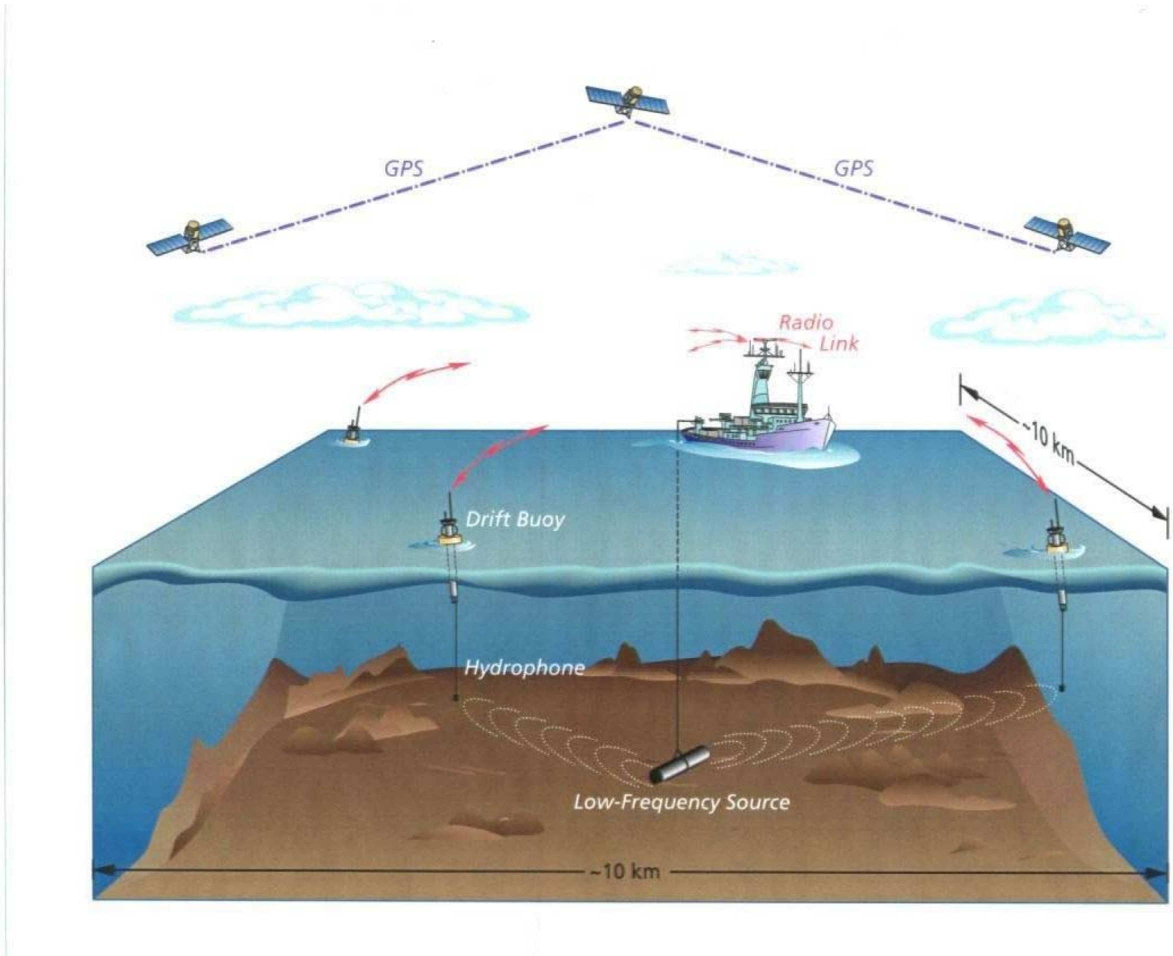

Figure 1: MOMAX experimental configuration.

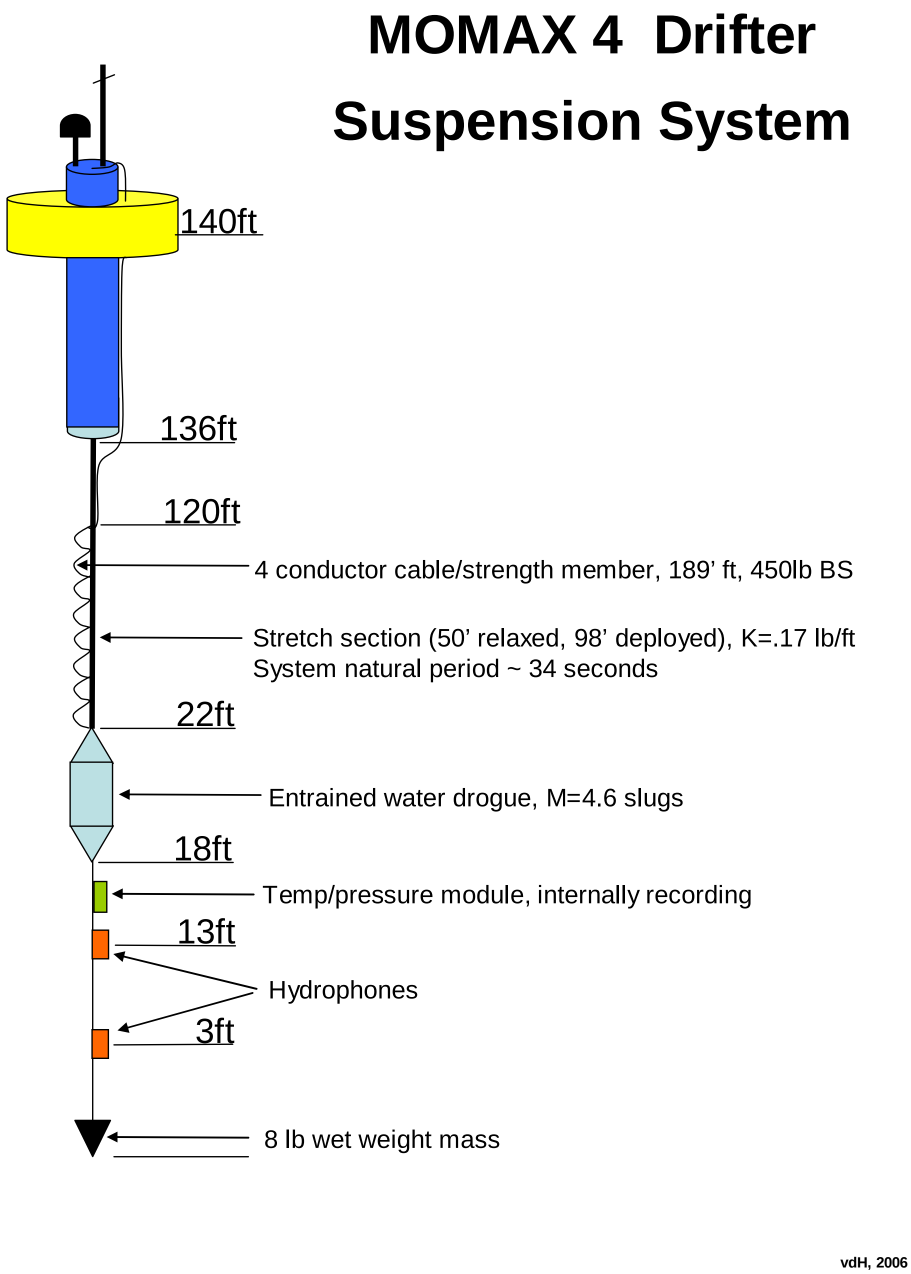

Figure 2: MOMAX buoy suspension system with temperature/pressure sensors and 2 hydrophones.

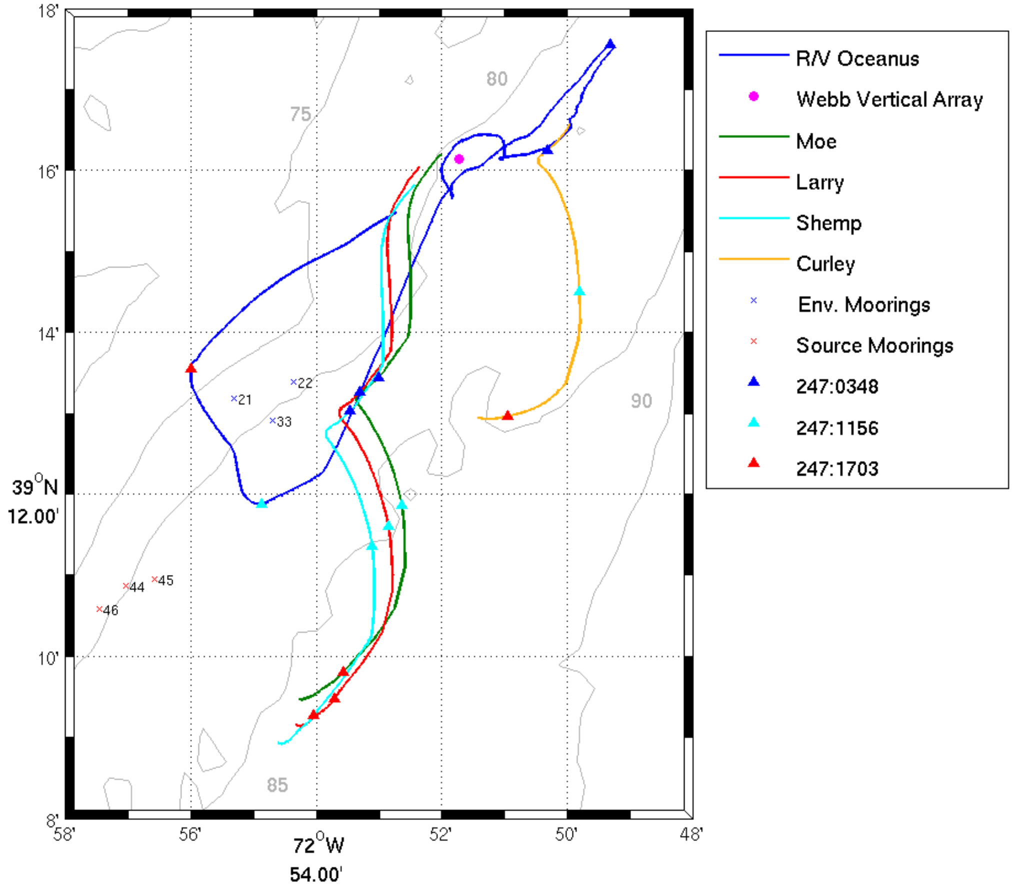

Figure 3: Tracks of source ship (R/V Oceanus) and 4 drifting buoys (Moe, Larry, Shemp, Curley) during SW06/MOMAX IV. Also shown in the experimental area are the Webb VLA and several temperature sensors (x21, x22, x33, x44, and x45) and source moorings (x44, x45, and x46).

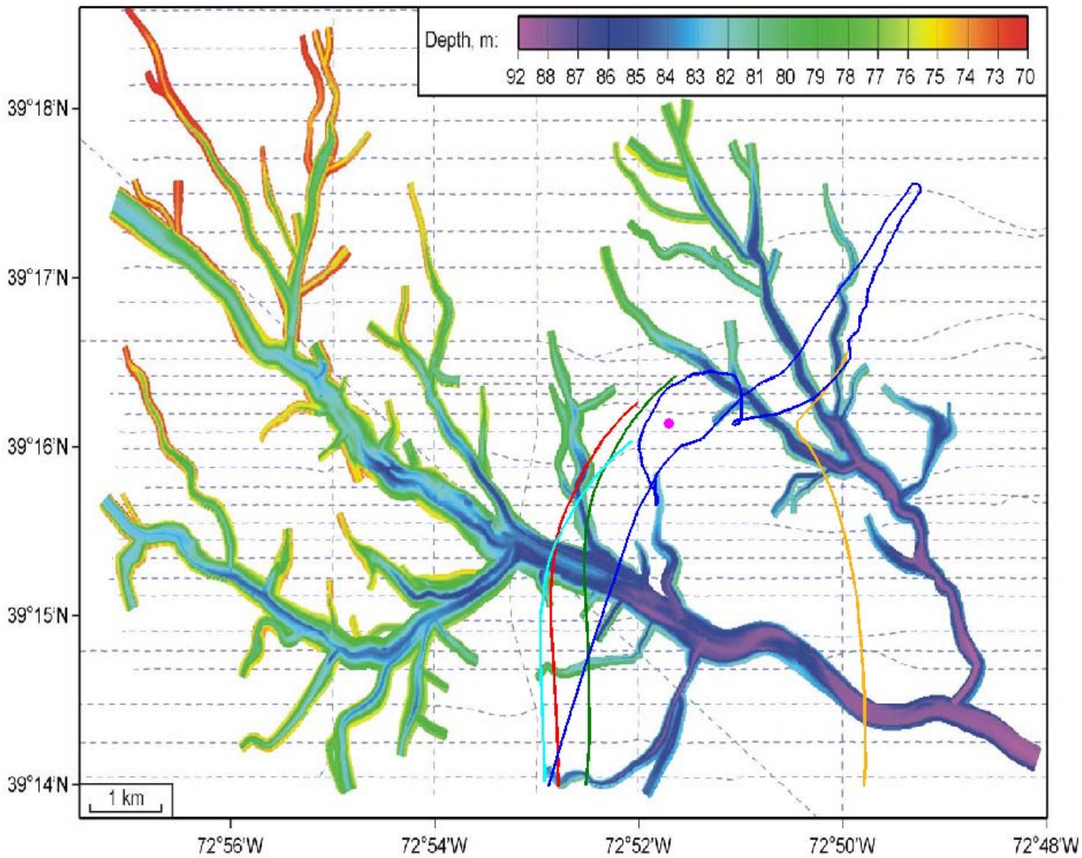

Figure 4: Tracks of source ship and 4 drifting buoys (see legend in Fig. 3) during SW06/MOMAX IV superimposed on subbottom river channel locations (J. Goff, private communication). Also shown is the Webb VLA (red dot).

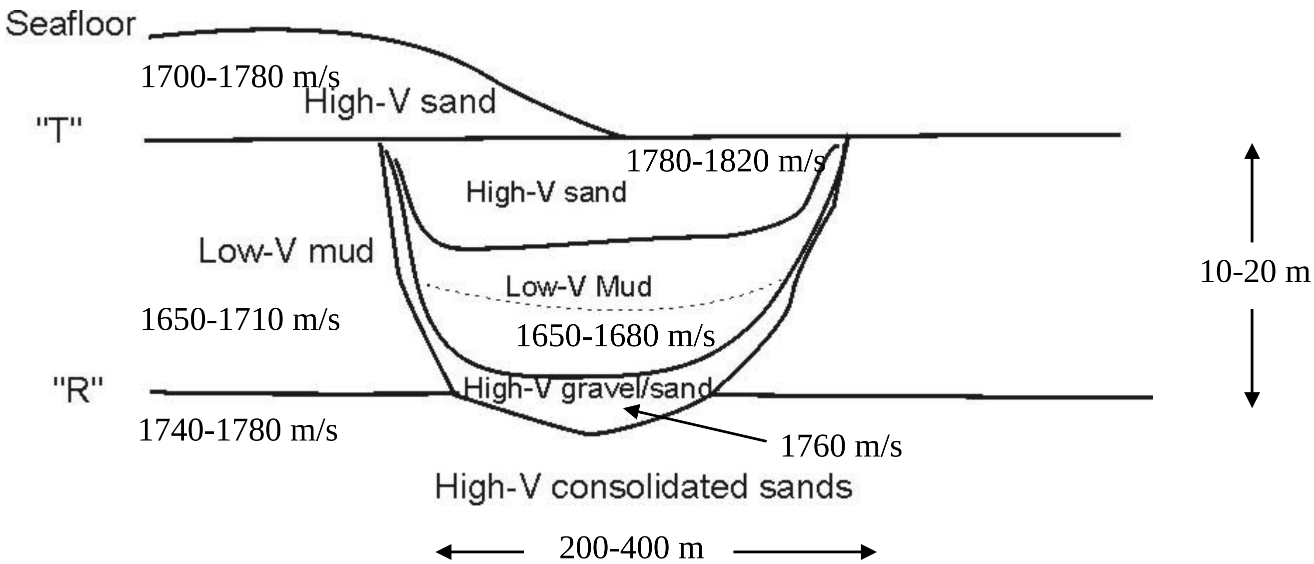

Figure 5: Typical subbottom river channel cross section with geoacoustic properties used as starting model for bottom inversion (J. Goff, private communication).

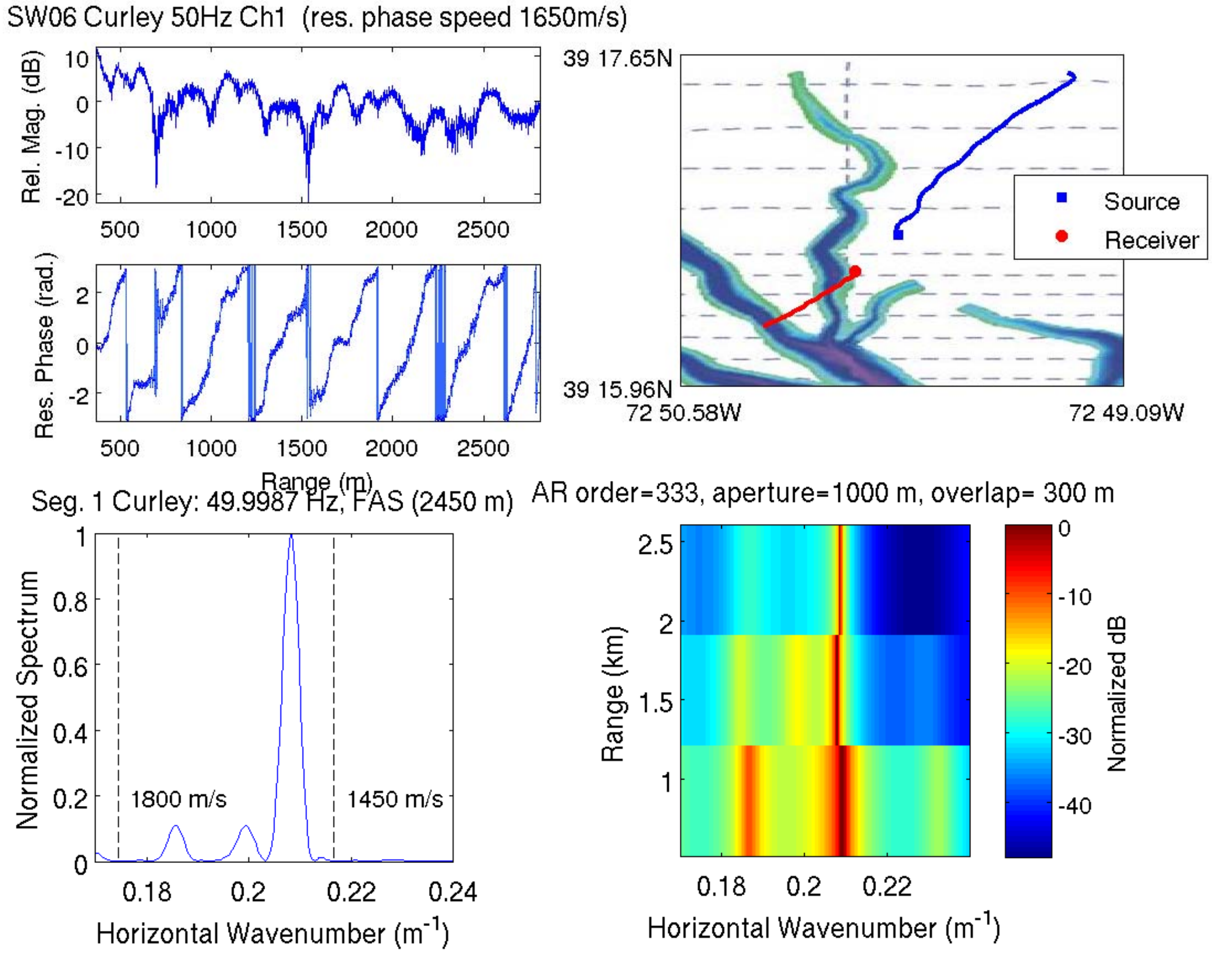

Figure 6: Summary of 50 Hz data received on Curley (hydrophone @ 40 m):
pressure magnitude and phase vs range (upper left),
source and receiver tracks superimposed on subbottom channel locations (upper right),
normalized wavenumber spectrum for entire range aperture (lower left),
autoregressive wavenumber spectrum vs range (lower right).

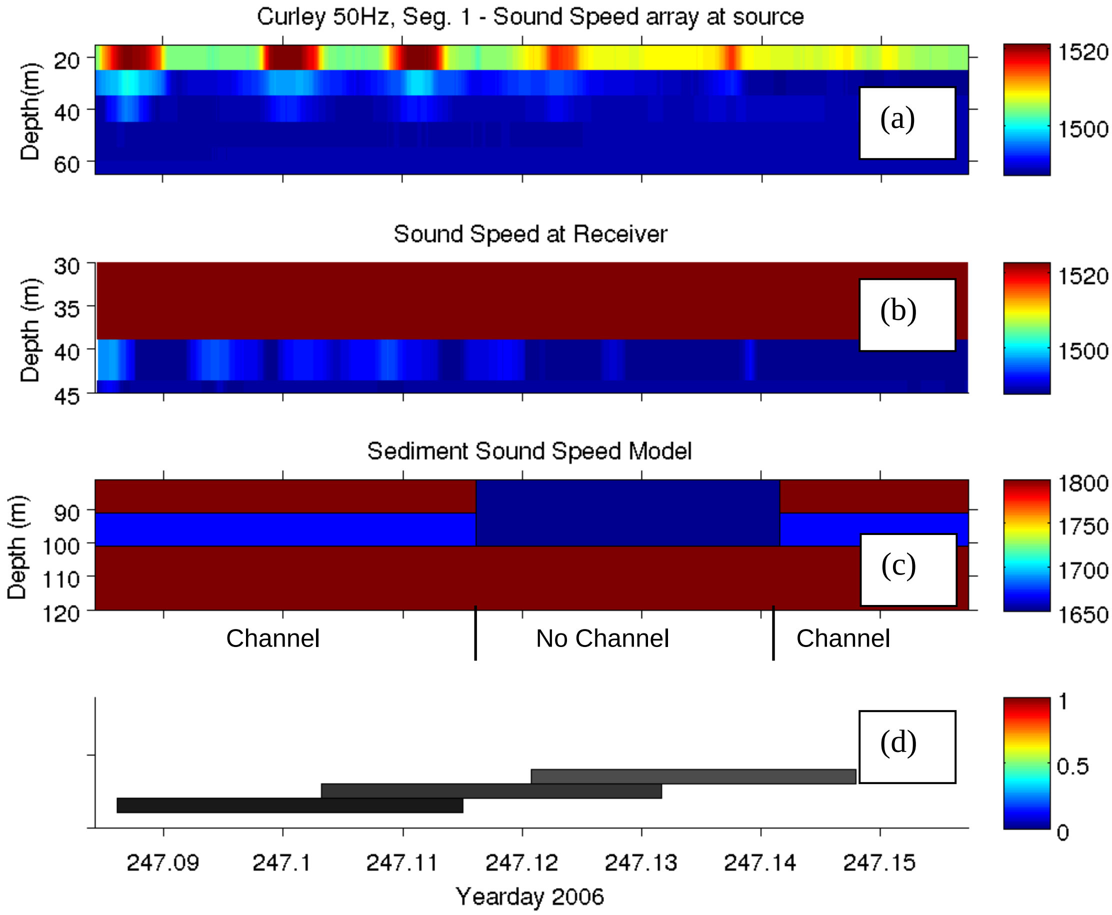

Figure 7: Summary of environmental variability associated with Curley 50 Hz data in Fig. 6:
(a) sound speed measured along cable suspending source at 60 m depth,
(b) sound speed measured at receiver depths of approximately 40 m and 43 m,
(c) sound speed in seabed based on starting model in Fig. 5,
(d) 3 processing apertures used to obtain autoregressive spectral estimate in Fig. 6.

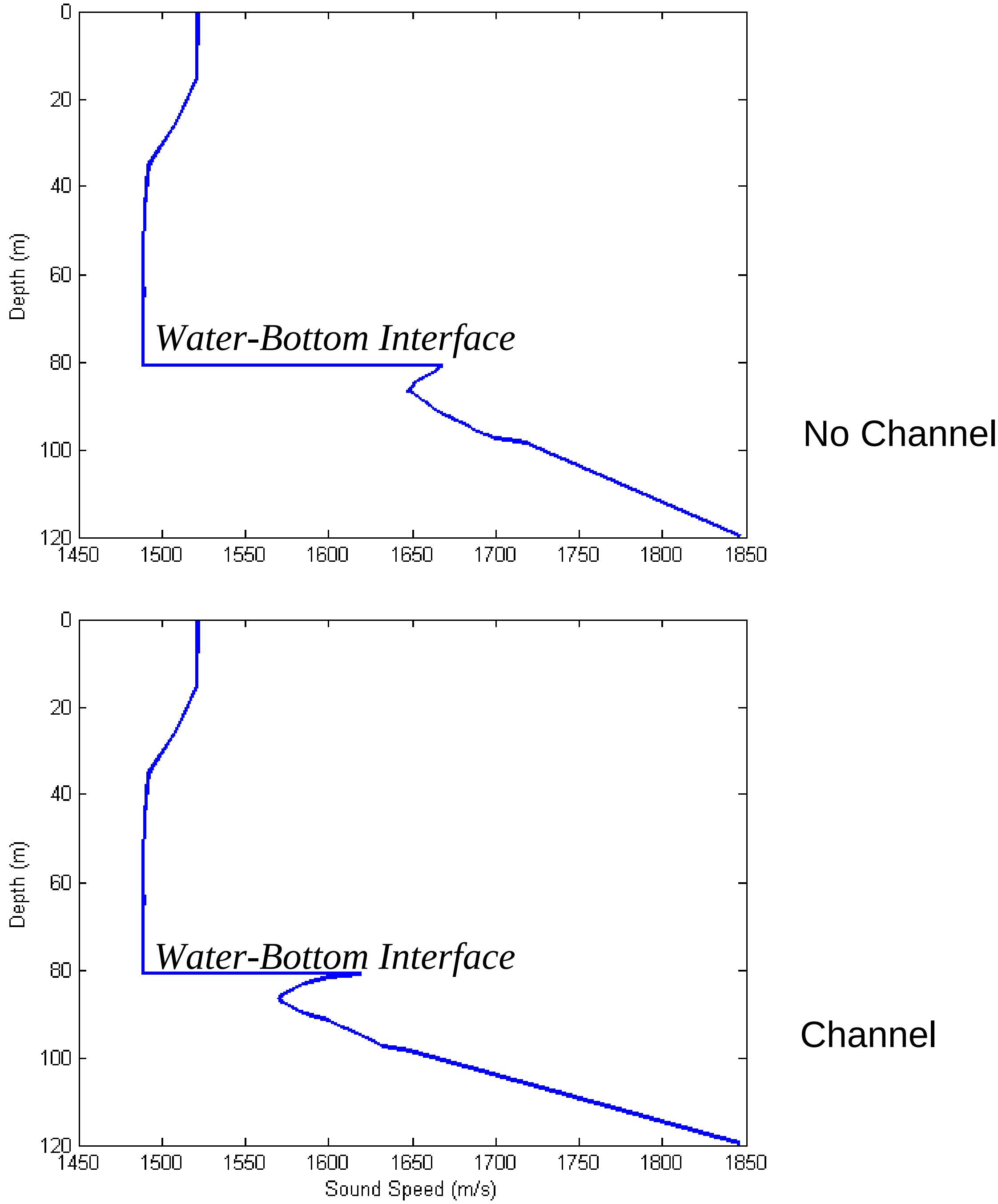

Figure 8: Inverted sound speed profiles in seabed:
No Channel results based on inversion results in Ohta et al. (2009),
Channel results based on iterative inversion approach using starting model in Fig. 5.

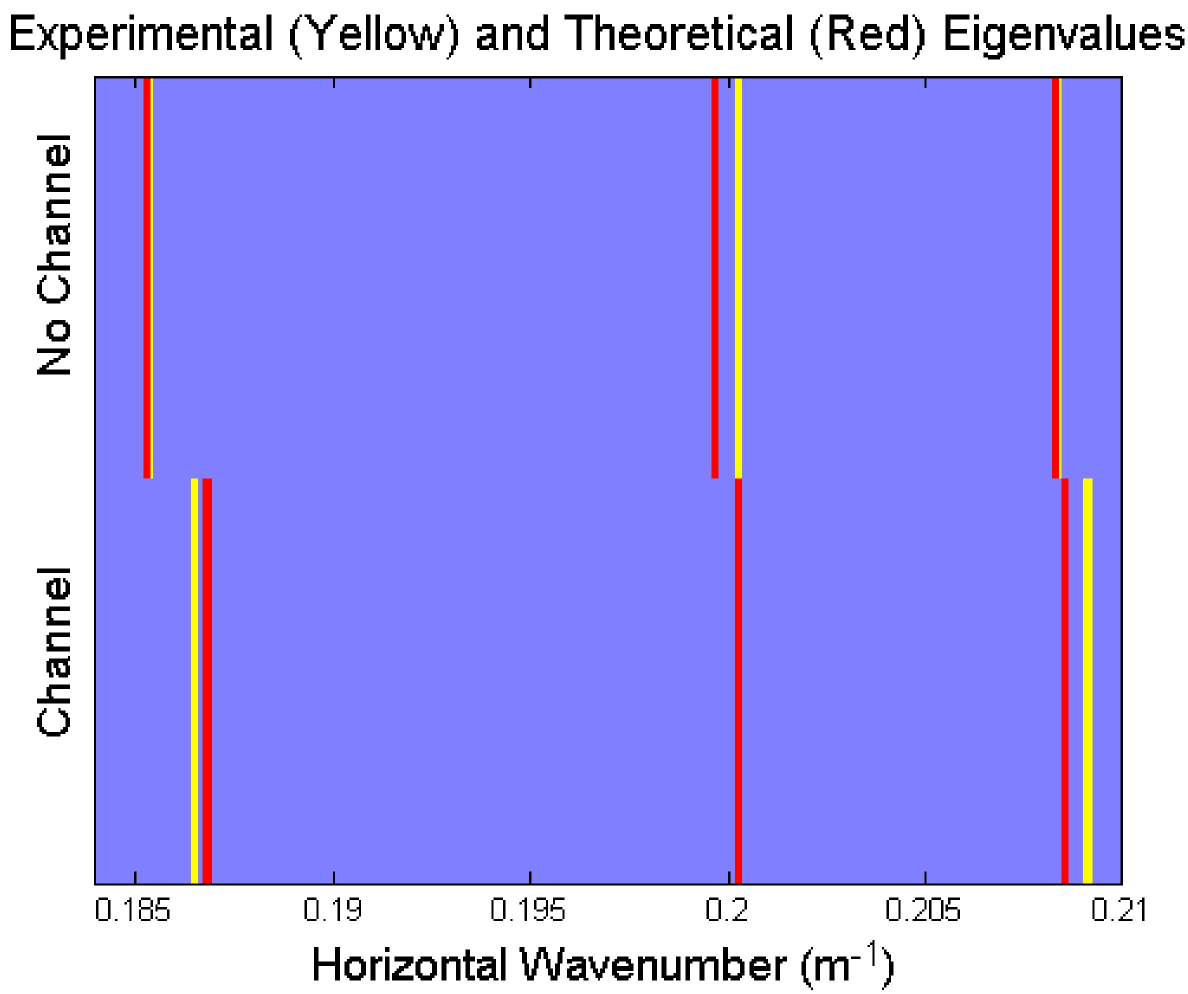

Figure 9: Comparison of experimental (yellow) and theoretical (red) eigenvalues computed with KRAKEN normal mode model using sound speed profiles in Fig. 8 as input data.

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PUBLICATIONS

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HONORS/AWARDS/PRIZES

G.V. Frisk, President-Elect of the Acoustical Society of America.